

# Trailing ( $L_5$ ) Neptune Trojans: 2004 KV18 and 2008 LC18

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## Abstract

The population of Neptune Trojans is believed to be bigger than that of Jupiter Trojans and that of asteroids in the main belt, although only eight members of this far distant asteroid swarm have been observed up to now. Six leading Neptune Trojans around the Lagrange point  $L_4$  discovered earlier have been studied in detail, but two trailing ones found recently around the  $L_5$  point, 2004 KV18 and 2008 LC18, have not been investigated yet. In this paper, we report our investigations on the dynamical behaviors of these two new Neptune Trojans. Our calculations show that the asteroid 2004 KV18 is a temporary Neptune Trojan. Most probably, it was captured into the trailing Trojan cloud no earlier than  $2.03 \times 10^5$  yr ago, and it will not keep this identity no later than  $1.65 \times 10^5$  yr in future. Based on the statistics on our orbital simulations, we argue that this object is more like a scattered Kuiper belt object. On the contrary, the orbit of asteroid 2008 LC18 is much more stable. Among the clone orbits spread within the orbital uncertainties, a considerable portion of clones may survive on the  $L_5$  tadpole orbits for 4 Gyr. The strong dependence of the stability on the semimajor axis and resonant angle suggests that further observations are badly needed to confine the orbit in the stable region. We also discuss the implications of the existence and dynamics of these two trailing Trojans on the Solar system history.

## 1 Introduction

The Trojans are celestial bodies moving on the same orbit as a planet, but around  $60^\circ$  ahead or  $60^\circ$  behind the planet close to the triangular Lagrange points  $L_4$  (leading) or  $L_5$  (trailing). By the original definition, only those asteroids on the so-called tadpole orbits are “real” trojans (Murray & Dermott 1999). Jupiter is the first planet known to host thousands of this kind of asteroids after the discovering of (588) Achilles in 1906. Several Trojan asteroids around Mars were discovered quite lately in 1990s (Bowell et al. 1990). Even another ten years later, the first Neptune Trojan 2001 QR322 was found (Chiang et al. 2003) to orbit around the  $L_4$  Lagrange point. And in the August of 2011, the first Earth Trojan was confirmed (Mainzer et al. 2011) and its dynamics was studied (Connors et al. 2011; Dvorak et al. 2012) very recently.

The trojan asteroids are of special interest not only because the dynamics of them is complicated, but also because their origin and evolution may bear important clues to the early history of our Solar system. Many studies, e.g. Nesvorný & Dones (2002); Marzari et al. (2003); Robutel & Gabern (2006); Robutel & Bodossian (2009); Dvorak et al. (2007, 2010); Zhou et al. (2009, 2011), have devoted to the dynamics of Trojan asteroids around different planets. In recent years, the origin of Trojans and the formation of the Trojans cloud began to attract more and more attentions (Morbidelli et al. 2005; Nesvorný & Vokrouhlický 2009; Lykawka et al. 2009, 2010) since the very well-known “Nice Model” (for a review, see for example Crida 2009) about the early history of the Solar system

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regards the existence and property of Jupiter trojans as one of the critical evidences of the theory (Morbidelli et al. 2005).

Before the discovery of asteroid 2008 LC18 by Sheppard & Trujillo (2010a), six Neptune Trojans (NT hereafter for short) have been observed<sup>1</sup>. But they are all around the leading Lagrange point  $L_4$ , about  $60^\circ$  ahead of Neptune. This is partly due to the fact that the trailing Lagrange point ( $L_5$ ) is nowadays in the Galaxy center direction. The background stars add difficulty to the discovery of asteroids in this “shinning” region. As the first NT orbiting around the  $L_5$  point, 2008 LC18 is of particular interest, not only because it is the first member of a possible asteroid swarm in which it resides, but also because a tricky way has been used to block out the strong background light from the Galaxy center. Following this success, another  $L_5$  NT (2004 KV18) was reported in July of 2011, adding the number of  $L_5$  NTs to two. As for orbital dynamics researching, these two findings make the first step of confirming the dynamical symmetry between the  $L_4$  and  $L_5$  points (Nesvorný & Dones 2002; Marzari et al. 2003; Zhou et al. 2009), and the high inclinations of their orbits (see Table 1) raise further the fraction of NTs on highly-inclined orbits (so far 3 out of total 8 NTs have inclination larger than 25 degrees). Both of these two points bring specific indications to the capturing process of NTs and the evolution of the planetary system in the early stage (Nesvorný & Vokrouhlický 2009; Lykawka et al. 2009, 2010). Meanwhile, the New Horizons<sup>2</sup> probe will travel through the sky region around Neptune’s  $L_5$  point in a few years, thus the study of this region is even more important than the one around  $L_4$ .

People meet difficulties in explaining the estimated 4:1 high inclination excess among the population of NTs (Sheppard & Trujillo 2006). Investigations on their dynamics show that the inclination of NTs is not likely excited *in situ* under the current planetary configuration. The only acceptable explanation seems to be that the NTs are captured rather than formed *in situ*, and the capture progress pumped up the Trojans’ orbits, resulting in both high inclination and high eccentricity (Nesvorný & Vokrouhlický 2009; Lykawka & Horner 2010). On the other hand, the NT orbit with eccentricity larger than 0.1 seems to be unstable, thus the NTs excited in the early days of the Solar system should have been expelled from the Trojan cloud (Zhou et al. 2009, 2011). This is the critical puzzle in the “capture origin” scenario.

Except for the newly found asteroid 2004 KV18, all other NTs have eccentricities below 0.1. The highly eccentric orbit ( $e = 0.184$ ) makes it so peculiar. Can it be the “smoking gun” to support the capture origin of Neptune Trojan cloud? Or, it is not a remnant from the original dynamically excited Trojan cloud, but just a passer-by on its journey from the trans-Neptune region to the inner interplanetary space. We take great interest to explore its dynamical properties to find some clues.

In this paper, we study in detail the dynamics of these two  $L_5$  Neptune Trojans. The paper is organized as follow. We give our model and method of numerical simulations in Section 2. The simulation results are summarized and discussed in Section 3 for 2004 KV18 and in Section 4 for 2008 LC18. Finally, we make the conclusions in Section 5.

## 2 Model and Method

The asteroids 2008 LC18 and 2004 KV18 have been observed at opposition for 2 and 3 times respectively, and their orbits have been determined. Their orbital elements, taken from the AstDyS (Asteroids - Dynamic Site) website<sup>3</sup>, are listed in Table 1. The uncertainties arising from the observation and orbital determination processes, are listed in the Table as well. In our previous papers (Zhou et al. 2009, 2011), we have constructed dynamical maps and resonant maps on the  $(a, i)$  and  $(a, e)$  planes to show the locations of important resonances that control the dynamics of NTs. If we find the positions of these two objects on the corresponding maps, we may get immediately the conjecture about their dynamical behaviors. For this sake, we transfer the orbital elements of these two objects to the right epoch JD=2449200.5 at which the maps were composed. They are given in Table 1 too.

<sup>1</sup>See the website of IAU: Minor Planet Center with URL <http://www.minorplanetcenter.net/iau/lists/NeptuneTrojans.html>

<sup>2</sup>[http://www.nasa.gov/mission\\_pages/newhorizons/main/index.html](http://www.nasa.gov/mission_pages/newhorizons/main/index.html)

<sup>3</sup><http://hamilton.dm.unipi.it>

Table 1: Orbital elements of asteroids 2008 LC18 and 2004 KV18, given at epoch JD=2455800.5 (2011-Aug-27) with respect to the mean ecliptic and equinox at J2000. The semimajor axes are given in AU, while the angular elements including inclination  $i$ , perihelion argument  $\omega$ , ascending node  $\Omega$  and mean anomaly  $M$  are in degrees. The elements and  $1\sigma$  variations are taken from the AstDyS (see text). For the sake of comparing with our previous results, the orbital elements at epoch JD=2449200.5 (see text for explanation) are listed in columns indicated by “Val4Com”.

Elements	2008 LC18			2004 KV18		
	Value	$1\sigma$	Val4Com	value	$1\sigma$	Val4Com
$a$	29.9369	0.02588	30.1010	30.1260	0.01088	30.3927
$e$	0.083795	0.002654	0.080360	0.183846	0.000797	0.190021
$i$	27.5689	0.003824	27.5144	13.6092	0.001336	13.5684
$\Omega$	88.521	0.0007854	88.549	235.6273	0.0004537	235.6852
$\omega$	5.1349	10.85	8.9773	294.5615	0.1789	295.7312
$M$	173.909	12.83	130.057	58.5939	0.09	18.1013

With the orbital elements of these objects, we perform numerical simulations to investigate their orbital evolutions and orbital stabilities. We adopt the Outer Solar System model, namely the gravitational system consisting of the Sun and four jovian planets from Jupiter to Neptune. The planets are in their current orbits and the NTs are assumed to be zero-mass particles. Taking into account the uncertainties in the orbital elements, to make our investigations convincing, it is necessary to consider some clone orbits around the nominal orbits of these objects. Using the covariance matrix given by the AstDyS website, we generate for each object a cloud of 1000 clone orbits in the 6-dimensional orbital elements space centered on the nominal orbit. The distribution of these elements, for 2008 LC18 as an example, can be seen in Fig. 4. The orbits are numerically simulated using the hybrid algorithm from the *Mercury6* package (Chambers 1999).

### 3 2004 KV18

For the asteroid 2004 KV18, 1000 clone orbits are integrated up to 10 Myr in both forward (to the future) and backward (to the past) directions. The integration time span (10 Myr) is chosen after some test computations, and it is long enough to show the behavior of the asteroid as being an  $L_5$  Neptune Trojan. In fact, according to the results in our previous papers (Zhou et al. 2009, 2011), the orbit of an NT can be stable only when its eccentricity is smaller than 0.12. The location of the nominal orbit of 2004 KV18 on the dynamical map at epoch JD=2449200.5 (figure 3 in Zhou et al. 2011), i.e.  $(a, e) = (30.3927, 0.190021)$  as listed in Table 1, reveals that this orbit locates far away from the stable region. Note that we did not show the dynamical map at the section of the exact inclination  $13.5684^\circ$ , but we had the maps for  $i = 10^\circ, 20^\circ$  in the paper and for  $i = 15^\circ$  not presented in the paper, and the continuity helps us draw the above conclusion.

#### 3.1 Lifespan as an $L_5$ Neptune Trojan

We have removed those clones whose semimajor axes exceed 100 AU in our simulations, because they have been practically ejected from the Solar system. By the end of the integration (10 Myr), 569 clones out of the total 1000 in the forward integrations, and 558 in the backward integration, survive (stay in the Solar system). The leftovers, however seem all on the very chaotic orbits and we believe they will escape the Solar system some time. Since our interests in this paper are mainly in the fate of the asteroid as a Neptune Trojan, we track the variable  $\sigma$  defined as:

$$\sigma = \lambda - \lambda_8$$

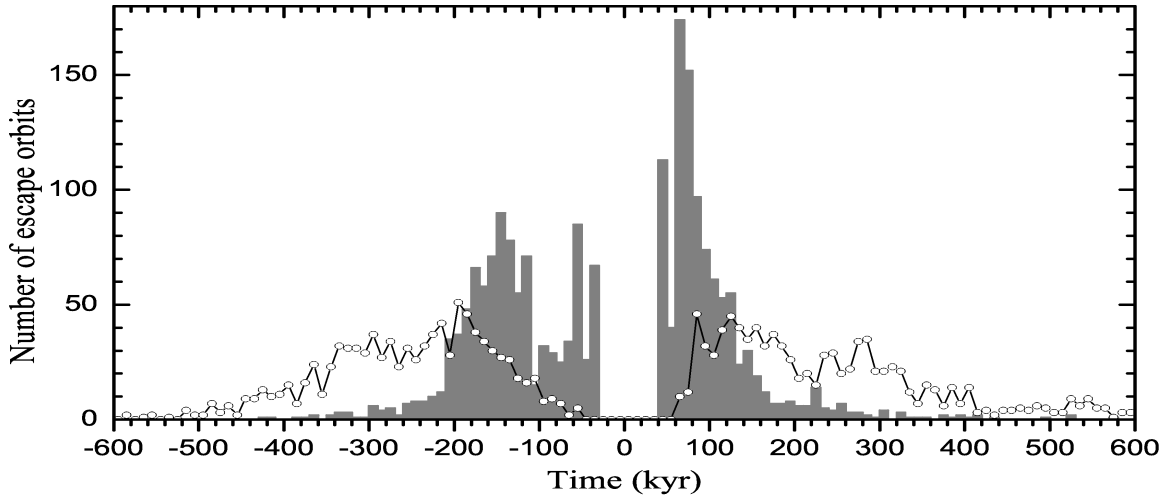


Figure 1: Number of escaping orbit per 10 kyr. The dark grey histogram in the background show the distribution of moments  $t_1$  when the clones leave the  $L_5$  Trojan region (see text), while the curves with open circles represent the distribution of  $t_2$  when the clone escape from the 1:1 MMR.

where  $\lambda$  and  $\lambda_8$  are the mean longitudes of the clone and Neptune, respectively. So  $\sigma$  is the critical argument of the 1:1 mean motion resonance (MMR) between the clone and Neptune. For an  $L_5$  trojan,  $\sigma$  librates around  $-60^\circ$  (or equivalently  $300^\circ$ ). When the librating amplitude<sup>4</sup> is not so large that  $-180^\circ < \sigma < 0^\circ$ , the trojan is on a “tadpole orbit”. If the amplitude gets larger resulting in  $\sigma < -180^\circ$ , the asteroid may still stay in the 1:1 MMR but turn to a “horseshoe orbit”. It is not a “Trojan” anymore according to the original definition (Murray & Dermott 1999). And if  $\sigma$  circulates, the asteroid leaves the 1:1 MMR. We define the time  $t_1$ , when for the first time  $\sigma$  goes beyond  $-180^\circ$  in our simulations, as the moment of a clone escaping from the Trojan cloud. When a clone begins to circulate for the first time at moment  $t_2$ , it is regarded as having escaped from the 1:1 MMR.

We summarize in Fig. 1 the distributions of  $t_1$  and  $t_2$  for the 1000 clones in both time directions. Judged by  $t_1$ , none of the clones keeps the  $L_5$  NT identity in 10 Myr in both time directions. Moreover, all of the clones leave the 1:1 MMR in our simulations (although some of them were recaptured into 1:1 resonance again by the end). This orbital instability is consistent with the conclusion drawn from locating the nominal orbit on the dynamical maps in our previous papers (Zhou et al. 2009, 2011).

By checking carefully the data, we find that the first escaping from the Trojan orbit ( $\sigma < -180^\circ$ ) in the forward integrations happens at  $\sim 46$  kyr, the escaping orbits pile up quickly making the first peak at  $\sim 48$  kyr. And soon after, the highest peak appears around  $\sim 73$  kyr. Till  $\sim 165$  kyr, 90% clones have left the  $L_5$  region. For the backward integrations, the distribution of  $t_1$  is more flat than that in the forward direction. The first escaping happens  $\sim -34$  kyr, and the first peak appears here. Very closely, another peak emerges at  $\sim -58$  kyr. About 30% of escapes are hosted by these two peaks. And a wide peak centered at  $\sim -155$  kyr contains nearly all the rest clones. Till  $-203$  kyr, 90% clones have escaped from the  $L_5$  tadpole orbits. Based on the above statistics, we may conclude confidently that the asteroid 2004 KV18 has been an  $L_5$  Neptune Trojan for at least 34 kyr and it will keep this identity for at least 46 kyr in future. But most probably, it’s neither a primordial nor a permanent member of the  $L_5$  NT cloud<sup>5</sup>. With a probability of 90%, it became an  $L_5$  NT no earlier than 203 kyr ago and it will leave the  $L_5$  region in less than 165 kyr.

Soon after leaving the tadpole orbits around the  $L_5$  point, the clones escape the 1:1 MMR in both time directions, as shown by the  $t_2$  distribution in Fig. 1. In fact, after leaving the  $L_5$  tadpole orbit and before its escaping from the MMR, a clone orbit may experience the horseshoe orbit, enter the tadpole

<sup>4</sup>In this paper, “amplitude” refers to the full range of  $\sigma$  variation, i.e. the difference between the maximal and minimal  $\sigma$  values.

<sup>5</sup>By “primordial” we mean that the asteroid has been in the Trojan region since very early, before or just after the planets attained their current orbits, no matter the asteroid was captured by or grown up with Neptune. By “permanent”, we mean that the asteroid will stay in the Trojan region until 4 Gyr later.

orbit around the  $L_4$  point, or even become a retrograde satellite of Neptune, but all these experiences only last for very short time. We will show some detail below.

### 3.2 Orbital evolution

To show the temporal evolution of the clone orbits, we plot in Fig. 2 the resonant angle ( $\sigma$ ), semimajor axis ( $a$ ), eccentricity ( $e$ ), and inclination ( $i$ ) of 50 clone orbits. These clones are selected arbitrarily (except the nominal orbit) from our 1000 samples. Clearly the orbits are chaotic, as the initially close-to-each-other orbits at time  $t = 0$  become separated quite soon.

In the top panel, we see that the resonant angle  $\sigma$  librates for several periods in both forward and backward directions before it's libration amplitude increases beyond  $180^\circ$  where the clone turns to the horseshoe orbit. The libration period  $T$  of a Trojan can be estimated through (see for example Murray & Dermott 1999)

$$T = 2\pi / \sqrt{\frac{27}{4}\mu}$$

where  $\mu$  is the mass of Neptune with respect to the Solar mass. This equation is only valid for tadpole orbits in the very vicinity of  $L_{4,5}$  points, and it leads to a period of 8.9 kyr for Neptune Trojan. The 2004 KV18 is quite far away from the  $L_5$  point with a  $\sigma$  amplitude  $\sim 100^\circ$  (see Fig. 2), and the libration period is  $\sim 10.7$  kyr. A clone always leaves the  $L_5$  region just after  $\sigma$  reaches the minimal value, and this explains the abruptly appearing peaks in Fig. 1 at  $t \sim -34$  kyr and  $t \sim 48$  kyr. Between these two peaks,  $\sigma$  finishes 7 whole librating periods. The libration amplitude must be tuned by some periodic effects (e.g. secular resonances), that's the reason some periodic features can be seen in the distribution of  $t_1$  and  $t_2$  in Fig. 1.

After leaving the  $L_5$  region in the future (or before being captured in the past), the clone may have different experiences before it's final escaping from the 1:1 MMR. It may librate with an amplitude larger than  $180^\circ$ , moving on a horseshoe orbit; it may shift to the tadpole orbit around the  $L_4$  point and become a leading Trojan; and it may behave like a retrograde satellite around Neptune with  $\sigma$  librating around  $0^\circ$  with a small amplitude. The nominal orbit and another highlighted orbit in Fig. 2 show clearly some of these possibilities. In a word, the asteroid 2004 KV18 is an  $L_5$  Neptune Trojan right now, but probably it was and will be in the  $L_4$  Trojan cloud, and it may change its identity several times in the time duration of being in the 1:1 MMR.

When a clone is on the tadpole orbit (either around the  $L_5$  or  $L_4$  point), its orbital evolution is more or less regular in this regime. For example, in the time range from  $-200$  kyr to  $70$  kyr, the nominal orbit is an  $L_5$  Trojan orbit as indicated by  $\sigma$ 's behavior, and we find its semimajor axis, eccentricity and inclination all behave regularly, as shown in Fig. 2. For another highlighted orbit (blue curves in Fig. 2), the tadpole stage is from  $-150$  kyr to  $140$  kyr ( $L_5$  first and  $L_4$  later, shifting at  $\sim 70$  kyr), again the regular evolutions in  $a$ ,  $e$  and  $i$  can be clearly recognized.

But the regular motion must be a transient phenomenon, because the orbit locates on the separatrix of the 1:1 MMR. This region is characterized by strong chaos induced by overlaps of the secondary resonances (see for example Michtchenko & Ferraz-Mello 1995). Moreover, comparing the orbital elements with the resonance map in our previous papers (figure 11 in Zhou et al. (2009) and figure 5 in Zhou et al. (2011)), we see that the 2004 KV18 may be strongly influenced by a combined resonance characterized by  $2f_\sigma - f_{2:1} + g_6 = 0$ , where  $f_\sigma$  and  $f_{2:1}$  are the frequencies of the resonant angle  $\sigma$  and the quasi 2:1 MMR between Neptune and Uranus, and  $g_6$  is the apsidal precession rate of Saturn.

As soon as the clone leaves 1:1 MMR, the orbital evolution will be very chaotic. This chaos arises from the overlap of one-order MMRs in the close vicinity of a planet's orbit (Wisdom 1980; Duncan et al. 1989). Meanwhile, because Neptune and Uranus are very close to the 2:1 MMR, some clones will enter the 2:1 MMR with Uranus immediately after it escapes the 1:1 MMR with Neptune. In fact the nominal orbit is in the 2:1 MMR with Uranus from  $70$  kyr to  $170$  kyr when its  $a$  librates around  $30.7$  AU with a small amplitude, as shown in the second panel of Fig. 2.

Due to the strong chaos, it is hard to predict precisely the long-term fate of the clones after they escape from the 1:1 MMR, or inversely in time, to trace back their origins before being capturing into

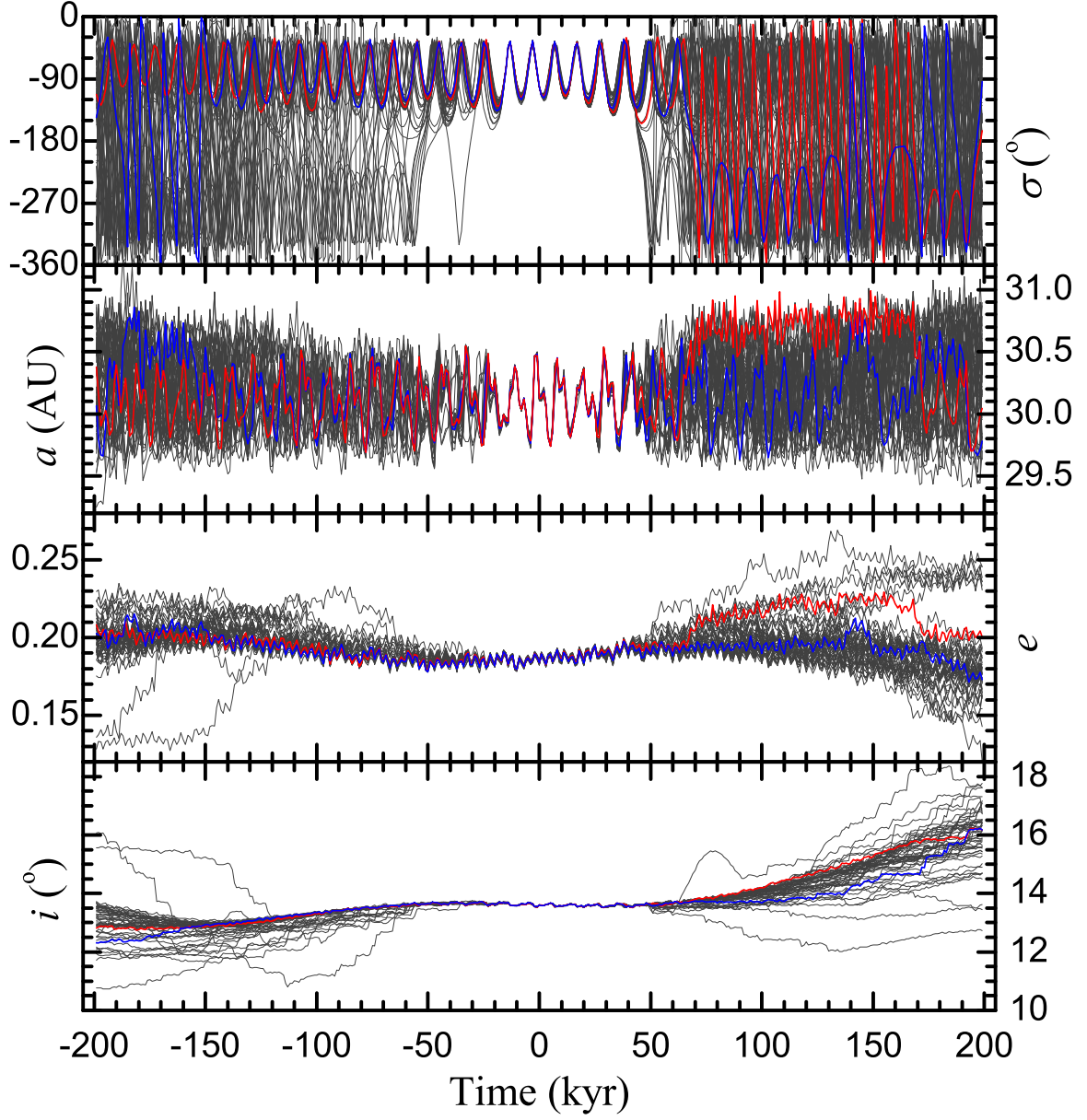


Figure 2: From top to down, we show the temporal evolution of the resonant angle ( $\sigma$ ), semimajor axis ( $a$ ), eccentricity ( $e$ ) and inclination ( $i$ ) of 50 clones. The nominal orbit is represented by the thick and red curves. And another arbitrarily selected orbit is highlighted and plotted in blue (see text).

this 1:1 MMR. However, we can still make some informative statistics on their evolutions as follow.

### 3.3 Past and future

Based on the behaviors of two variables, namely the semimajor axis  $a$  and resonant angle  $\sigma$ , we divide the clone orbits into seven categories:

- Tadpole orbits, TD for abbreviation
- Horseshoe orbits, HS for abbreviation
- Retrograde satellite, RS for abbreviation
- Centaurs, CT for abbreviation
- Transneptunian objects<sup>6</sup>, TNO for abbreviation
- Passing by orbits, PB for abbreviation
- Ejected objects, EJ for abbreviation

Actually, the first three all belong to co-orbital motions. They have similar  $a$ , but differ from each other by the libration center of  $\sigma$ :  $\pm 60^\circ$  for TD,  $\pm 180^\circ$  for HS, and  $0^\circ$  for RS. As for Centaurs and TNOs, our definition is not so rigid as in common sense. For a clone whose  $\sigma$  does not librate, we simply check if its semimajor axis is larger or smaller than the upper or lower boundary of Trojan semimajor axis. This boundary is estimated through  $\frac{d}{D} \approx \sqrt{3\mu} a_8$  where  $d$  and  $D$  represent the amplitudes of  $a$  and  $\sigma$ , respectively, and  $a_8$  is the semimajor axis of Neptune. Here the angular boundary  $D$  is set to be  $70^\circ$  according to our previous study (Zhou et al. 2009), and the upper and lower boundaries of  $a$  are then defined by  $a_8 \pm d$ . The orbits located out of the upper boundary are regarded as TNOs, while CTs are those inside the lower boundary. If in a watch window the semimajor axis of a clone excurses both sides of the Trojan boundaries, it is assigned to the PB category. And finally, those with semimajor axis larger than 100 AU are regarded as being ejected from the system. We set the watch window to be 50 kyr, covering about 5 full librating periods of a tadpole orbit. Over the 10 Myr's duration of our simulations, ten evenly distributed windows are set. We check the 1000 clones in every window and the statistical results are illustrated in Fig. 3.

The forward and backward integration give more or less the same results in Fig. 3. Note that though we find RSs when closely examining the orbits, no RS appear in Fig. 3. Generally the RS phase for a clone orbit lasts only for a very short duration, and it cannot be recognized by our numerical categorization code. On one hand, we need longer window width to assure the orbits type; on the other hand, we need shorter time interval to avoid type mixing in a window. Surely such a dilemma also causes deviations to other categories, but not too much.

As Fig. 3 shows, the number of PBs and all co-orbital orbits (TD and HS) decreases with time, indicating that these orbital types are only temporary phases, and not likely to be the final destiny of 2004 KV18. While the portion of TNOs and CTs seem not change much after  $3 \times 10^5$  yr, implying that they may be the potential final destinies for 2004 KV18. Since the number of CTs is smaller than that of TNOs, and this number decreases slightly with time, we argue that it's more possible that 2004 KV18 was ever and will end as a TNO than as a Centaurs.

## 4 2008 LC18

At first glance, the asteroid 2008 LC18 is more like a typical NT than 2004 KV18, because it has a small eccentricity. Locating the nominal orbit  $(a, e, i)$  at epoch JD=2449200.5 on the dynamical maps in our previous papers (figure 3 in Zhou et al. 2011), we know that it is on the edge of stable

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<sup>6</sup>Roughly speaking, Transneptunian Objects (also known as the “Kuiper belt objects”) are those celestial objects whose semimajor axes are larger than that of Neptune; and Centaurs are celestial objects with semimajor axes between that of Jupiter and Neptune.

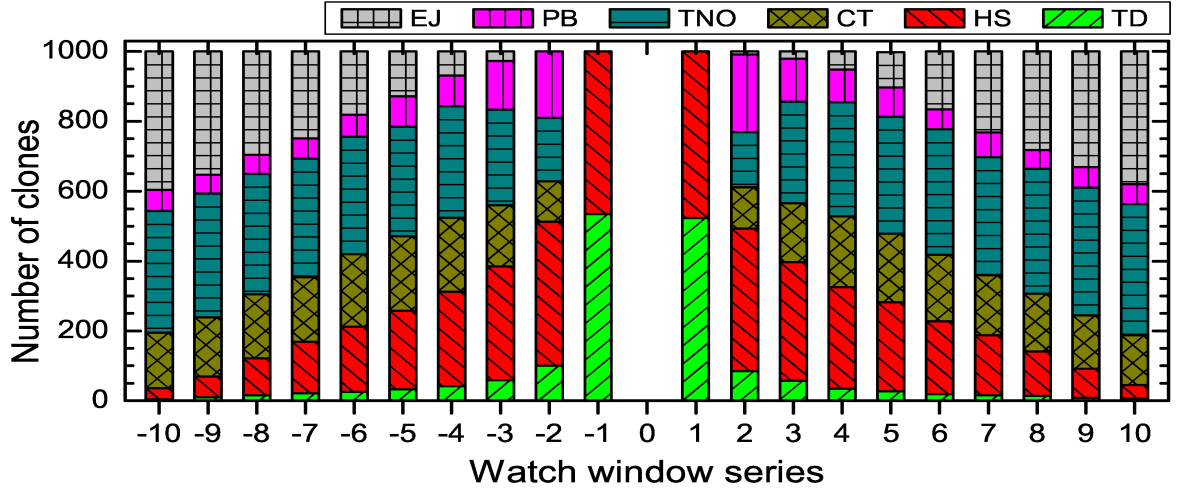


Figure 3: States of the 1000 clones in ten watch windows (50 kyr each) evenly spreading in the 10 Myr duration of both the forward and backward integrations. The series numbers of windows are in the temporal sequence.

region. The *spectral number*<sup>7</sup> (SN) of it is  $\sim 50$ . This SN is nearly the same as the ones for the  $L_4$  NTs, 2005 TO74 and 2001 QR322, but is larger than the SNs for other four  $L_4$  NTs (2004 UP10, 2005 TN53, 2006 RJ103 and 2007 VL305). So the stability of 2008 LC18 is comparable to 2005 TO74 and 2001 QR322, whose orbits have been discussed in our previous paper (Zhou et al. 2011). As a matter of fact, in the paper reporting the detection of 2008 LC18, Sheppard & Trujillo (2010a) mentioned that all the orbits of known NTs by then (seven NTs except for 2004 KV18) “are stable for the age of the Solar system”. On the contrary, 2004 KV18 just discussed in previous section, has an  $SN > 100$ , indicating a very chaotic thus unstable orbit.

The orbit of 2008 LC18 is less precisely determined compared to 2004 KV18, as indicated by the larger  $1\sigma$  variations in Table 1. Using the same method for 2004 KV18, a cloud of 1000 clone orbits is generated around the nominal orbit in the 6-dimensional orbital elements space. The initial conditions ( $a, e, i$  and  $\sigma$ ) of these clones can be seen in Fig. 4. We integrate these clone orbits for  $4 \times 10^9$  yr (4 Gyr, roughly the lifetime of the Solar system) in both forward and backward directions. The results are presented below.

#### 4.1 Initial conditions and orbital stability

We monitor the resonant angle  $\sigma$  of each clone orbit in the numerical simulations. When  $\sigma < -180^\circ$  for the first time ( $t_1$ ), the identity of the clone as an  $L_5$  NT is regarded as ended. In our calculations, we found that as soon as a clone deviates from the tadpole orbit it will leave the 1:1 MMR very soon later. Therefore, we ignore the moment of escaping from the 1:1 MMR, i.e.  $t_2$ , but focus only on  $t_1$  in this part.

Among the 1000 clones, for both forward and backward integrations, the first escaping from the  $L_5$  Trojan region happens at  $2 \times 10^5$  yr, but most of clones survive in the  $L_5$  cloud beyond  $10^8$  yr. In Fig. 4 we show the dependence of the lifetimes ( $t_1$ ) of clone orbits on the initial conditions. Since our calculations reveal a good temporal symmetry, i.e. the results from the backward integrations are nearly the same as the results from the forward integrations (it can be seen clearly in Fig. 5 too), we show in Fig. 4 only the case for the forward integration.

All points with different colors, including the black points indicating the most stable orbits surviving 4 Gyr on the Trojan orbits, spread uniformly in the  $(e, i)$  cloud of initial conditions in the left panel of Fig. 4. This uniform distribution indicates that within the orbital elements’ uncertainty ranges, the lifetime ( $t_1$ ) has no relation to either the initial eccentricity  $e$  or the initial inclination  $i$ .

<sup>7</sup>The spectral number is an indicator indicating the regularity (or, stability) of an orbit. A regular (thus stable) orbit has a small SN while a chaotic (unstable) orbit has a large SN. See our previous paper (Zhou et al. 2009) for the definition.



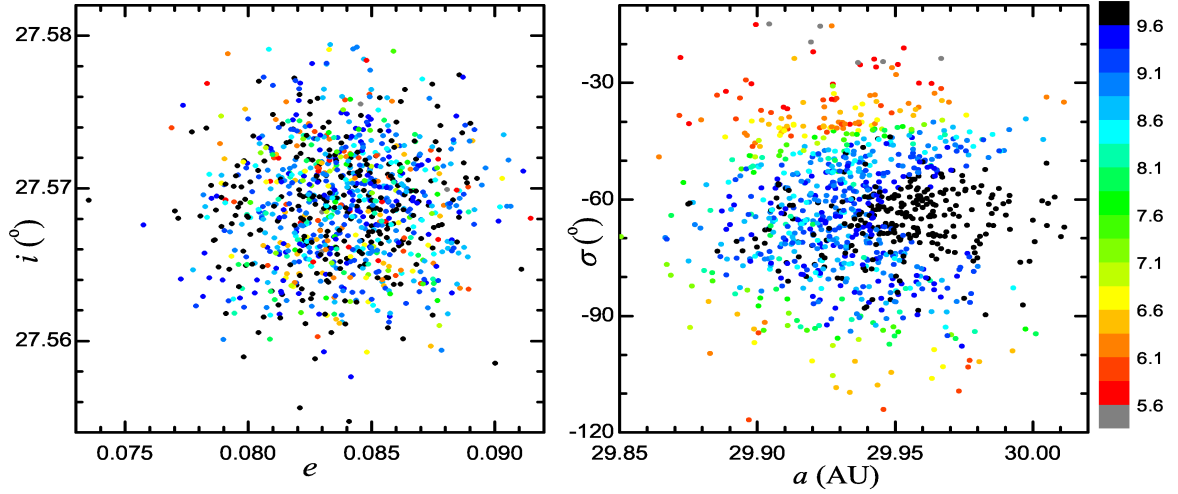


Figure 4: The initial conditions of clone orbits of 2008 LC18. The color code indicates the lifetime of the clone as an  $L_5$  NT (as the  $t_1$  in Fig. 1, in logarithmical scale). Those orbits staying on the  $L_5$  Trojan orbits for the whole simulation timespan (4 Gyr) are indicated by black dots.

We also check carefully the dependence of lifetime on the initial angular variables ( $\omega, \Omega, M$ ) and find that the stability does not have apparent relevance to these angular orbital elements either (within the error ranges, of course). Nevertheless, the stability depends on the summation of  $\omega, \Omega$  and  $M$ , namely the mean longitude  $\lambda = \omega + \Omega + M$ . More precisely, it depends on the resonant angle  $\sigma = \lambda - \lambda_8$ , as shown in the right panel of Fig. 4.

Also in this picture, the dependence on the semimajor axis is manifest. The color points make a layered structure. The most unstable orbits occupy the outer layer to the left, especially, we find that both too large ( $\sigma > -40^\circ$ ) and too small ( $\sigma < -100^\circ$ ) initial  $\sigma$  lead to unstable motion. Meanwhile, nearly all the most stable orbits concentrate in the inner layer to the right. The gathered black points form a triangle in the region of middle  $\sigma (\sim -65^\circ)$  and large  $a (> 29.93 \text{ AU})$ , and no color points exist in this triangle.

In fact, we know from our previous studies (Zhou et al. 2009) that the libration amplitude of  $\sigma$  is related to the initial semimajor axis. The further the initial  $a$  is away from the resonant center, the larger the  $\sigma$  amplitude is. Thus, the layered structure in the right panel may be equivalent to the vertical stripe structure in the dynamical maps on the  $(a, e)$  plane (figure 3 in Zhou et al. 2011), where the initial  $\sigma$  is fixed. The “C type” secular resonances (Zhou et al. 2011) were found to be responsible for the vertical structures. Recalling the position of 2008 LC18 on the  $(a, e)$  and  $(a, i)$  planes, we find that layered structure on the  $(a, \sigma)$  plane in Fig. 4 is probably due to one of the “C type” resonance:  $4f_\sigma - 2f_{2:1} + g_6 + g_7 = 0$ .

The probability of finding Neptune Trojans in the stable region should be much higher than in the unstable region, thus the 2008 LC18 is expected to be on a stable orbit. We would argue that further observations in future will constrain its orbit to the stable region, particularly, the semimajor axis and the corresponding resonant angle to the triangle on the  $(a, \sigma)$  plane in Fig. 4, as we mentioned above.

Starting from the 1000 clones and after 4 Gyr’s orbital evolution, there are still 262 clones surviving in the  $L_5$  region ( $t_1 > 4 \text{ Gyr}$ ) in the forward integration. As for the backward integration, 252 orbits survive. In a word, more than 25% of clones stay on the tadpole orbit around the  $L_5$  point till 4 Gyr in both forward and backward directions. The escaping of clones from the  $L_5$  region happens in a wide time range beginning from  $2 \times 10^5 \text{ yr}$ . The number of clones that survive on the tadpole orbits decreases with time. We plot in Fig. 5 such declines of clone numbers for integrations of both directions.

Two curves for the forward and backward integrations in Fig. 5 coincide with each other, implying the nearly exact symmetry between two temporal directions. From the profiles of these curves, two stages of escapes intersecting with each other at  $\sim 10^7 \text{ yr}$  can be readily recognized. In the first stage, about 15% of clones ( $\sim 150$  clones) escape from the  $L_5$  region, quickly. While in the second stage,

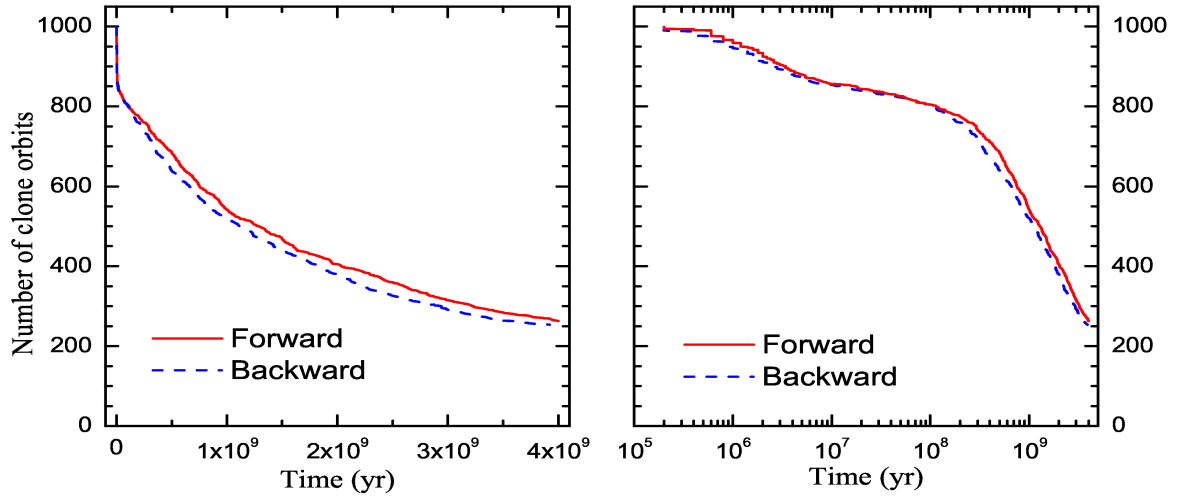


Figure 5: The number of clones that survive in the  $L_5$  cloud decreases with respect to time. In the left panel, the time is in linear scale while in the right panel it's in logarithmical scale. The solid red curves are for the forward integrations, and the dashed blue curves for the backward integrations.

the number of surviving clones decreases slowly. As indicated by the escape times (color) in Fig. 4, nearly all the clones that escape in the first stage have initial resonant angles either  $\sigma_0 > -40^\circ$  or  $\sigma_0 < -100^\circ$ . The clones escaping in the second stage on the other hand have  $-40^\circ < \sigma_0 < -100^\circ$ . In fact, as the dynamical maps in our previous papers (figure 3 in Zhou et al. 2011) show, the stable region is separated from the unstable region by a sharp edge, i.e. the intermediate area is very narrow. Thus it's natural to see that those orbits initially locating in the unstable region escape quickly making the quick decrease in the first stage in Fig. 5, while those orbits in the stable region escape slowly in the second stage. We believe that 2008 LC18 is a typical NT rather than a temporary NT like 2004 KV18. Further observations will reduce the uncertainties of the orbit and probably exclude those unstable clone orbits escaped in the first stage. Then the decay in the second stage will give the “proper” surviving probability of this objects in the  $L_5$  region.

Moreover, for those orbits initially in the stable region, their orbital elements may diffuse very slowly on the dynamical map and the instability can set in “abruptly” when the orbit crosses the narrow transitional area. Such an example of sudden escape from the  $L_5$  region is shown in the following section.

## 4.2 Orbital evolution

We have shown in the above section the ensemble behavior of clone orbits, and we will turn to the evolution of individual orbits now. But in fact, the orbital evolution of clones of 2008 LC18 is plain. As an example, we illustrate in Fig. 6 the temporal evolution of the nominal orbit of 2008 LC18.

From the behavior of resonant angle  $\sigma$  in the top panel of Fig. 6, the nominal orbit will leave the  $L_5$  Trojan region in about 3.505 Gyr, and it was captured to the  $L_5$  tadpole orbit about 1.678 Gyr ago. During its being an  $L_5$  Trojan, the semimajor axis, eccentricity and inclination behave very regularly, varying with small amplitudes. Particularly, the amplitude of  $\sigma$  is smaller than  $40^\circ$  in most time of its life. No apparent secular variations of  $a$ ,  $e$ ,  $i$  or  $\sigma$  can be observed in the time range when it is on the tadpole orbit as a Trojan. As we mentioned above, the chaos seems to set in suddenly. This is due to the fact that the border between the stable and unstable region is narrow, a small deviation from the stable region may result in destroying of the stability.

Actually, all those stable orbits that survive on the tadpole orbits in both time directions for 4 Gyr behave in a similarly regular way as the nominal orbit in the Trojan phase from  $-1.678$  Gyr to 3.505 Gyr. Their semimajor axes oscillate between 29.98 AU and 30.4 AU, their eccentricities are always smaller than 0.12, their inclinations librate around  $26^\circ$  with amplitudes smaller than  $4^\circ$ , and their resonant angles librate around  $-60^\circ$  with amplitudes  $\sim 30^\circ$ .

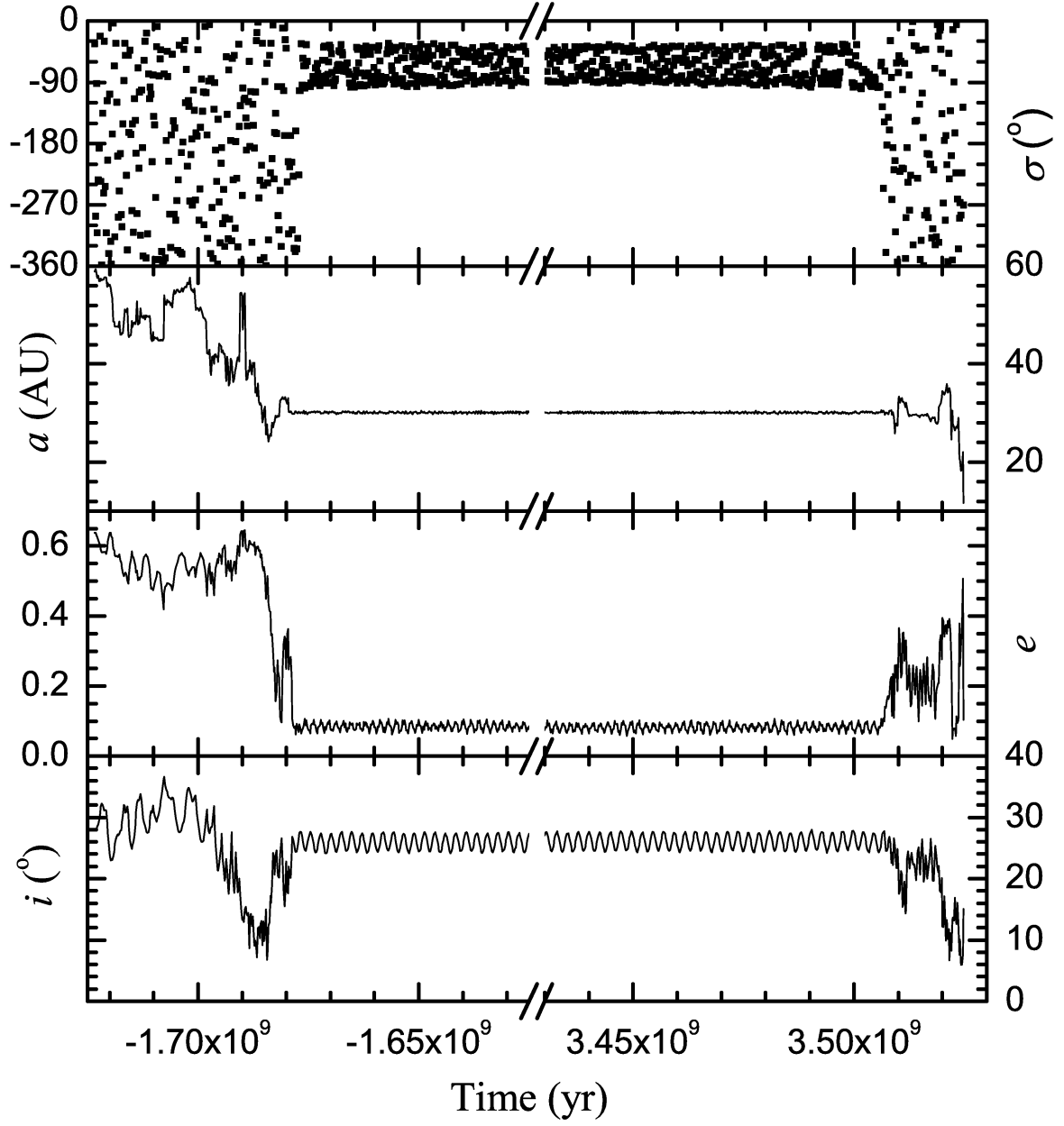


Figure 6: Temporal evolution of the resonant angle ( $\sigma$ ), semimajor axis ( $a$ ), eccentricity ( $e$ ) and inclination ( $i$ ) of the nominal orbit of 2008 LC18. Note the break in abscissa axis.

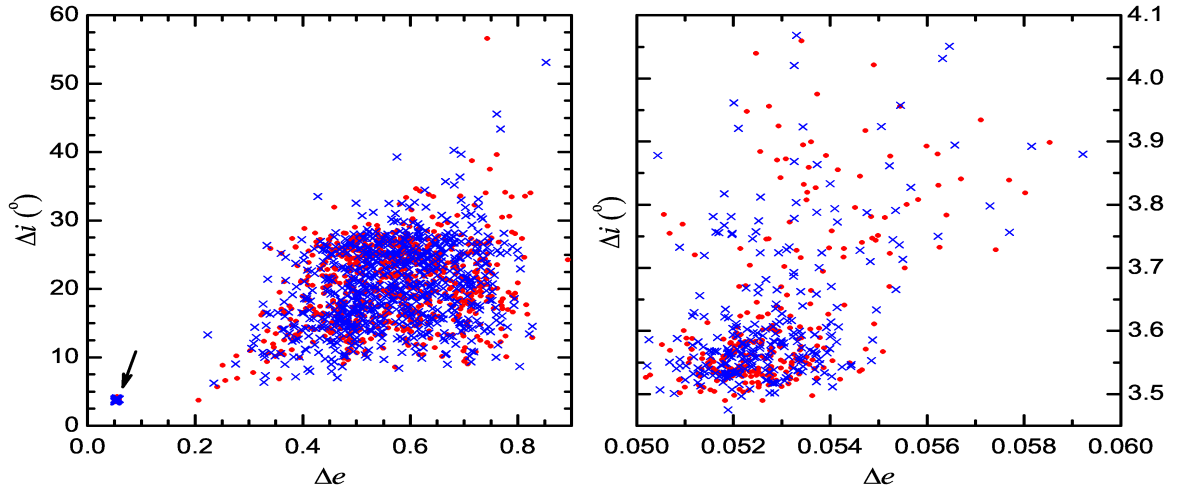


Figure 7: The variations of the eccentricity and inclination of clone orbits. The red solid circles are for the forward integrations and the blue crosses for backward integrations. The right panel shows the variations for those stable orbits surviving in the  $L_5$  region for 4 Gyr. It is an enlargement of the lower left corner of the left panel, indicated by an arrow (see text).

The second panel of Fig. 6 shows that the semimajor axis of the nominal orbit was beyond the orbit of Neptune before it was captured into the Trojan cloud, and it will be inside Neptune’s orbit after it leaves the  $L_5$  region. Therefore, it had become a NT from a scattered Transneptunian Objects (TNO) and it will turn to a Centaurs finally in future. However, it is worth noting that we may draw conclusions from our calculations about the destiny of these clones 4 Gyr later in future, but no solid conclusions can be made about their origins 4 Gyr ago in the past. The Solar system currently is quite “clean”, but 4 Gyr ago the orbits of planets probably had not been settled down and the planetesimal disc or even the gas disc still existed. Even though the computing error (roundoff error and model error) could be ideally controlled and ignored absolutely, the origin of a NT cannot be determined by tracing back its orbit through backward integration, because the exact circumstances at that time are far from being understood.

### 4.3 Inclination excited *in situ*?

Although the eccentricity of 2008 LC18 is small ( $\sim 0.08$ ), its inclination is quite high ( $\sim 27.5^\circ$ ), suggesting a typical excited orbit. The high inclination of some NTs is an important puzzle and perhaps also a key clue for the understanding of their origins and orbital evolutions. Based on our calculations for those 1000 clones, we discuss in this part the excitation of NT orbits, particularly, we will check the possibility of inclination being pumped up *in situ*.

The resonant maps (figures 5, 6, 7 in Zhou et al. 2011) reveal that numerous secular resonances involve in the orbital dynamics of NTs, even in the stable region of the orbital elements space. The effects of these resonances may be not so strong that the orbital stability of NTs may not be destroyed in the age of the Solar system. But they may drive the orbits of NTs to diffuse slowly in the elements space, so that a primordial NT may attain the high inclination through this slow diffusion. To clarify whether this process is responsible for the inclination of 2008 LC18, we examine the eccentricity variation  $\Delta e$  and inclination variation  $\Delta i$  of clone orbits during the simulations. Here  $\Delta e$  and  $\Delta i$  are the full varying ranges of eccentricity and inclination, defined as the differences between the maximal and minimal values of  $e$  and  $i$  in the whole simulations. The results are summarized in Fig. 7.

In the left panel of Fig. 7, clone orbits are divided into two separated groups. One group extends from  $\Delta e = 0.2$  to  $\Delta e = 0.85$ , and the other one is confined in a small area at low  $\Delta e$  and low  $\Delta i$ , indicated by the arrow in the picture. We pick out all the stable orbits surviving 4 Gyr in our simulations in both integration directions and plot their variations of  $e$  and  $i$  in the right panel of Fig. 7. Apparently, the above mentioned group of orbits locating in the lower left corner of the left

panel just consists of those stable orbits exactly. So, all the stable orbits have small eccentricity and inclination variations, i.e.  $0.05 < \Delta e < 0.06$  and  $3.45^\circ < \Delta i < 4.10^\circ$ . For those stable orbits, the inclination neither decreases significantly in the backward integration nor increases in the forward integration. Hence the inclination of 2008 LC18 seemingly has not arisen under the current configuration of the Solar system.

However, those unstable orbits occupy the lower right half of the left panel in Fig. 7, reflecting that most of them experience large eccentricity variations. A carefully examining on the orbits reveals that the eccentricity variation is caused either by crossing through MMRs (between clones and planets) or by close encounters of the clones with planets. And both of these two mechanisms work only when the clones are outside the Trojan phase. Generally, the increased eccentricity of a clone will result in further close encounters with planets. The inclination may obtain large variation in these encounters. That is the reason why large inclination variation is always accompanied by large eccentricity variation. On the contrary, the lack of orbits in the upper left region of the picture shows clearly that no inclination excitation could happen without the eccentricity excitation.

To the question of whether the inclination of 2008 LC18 can be excited *in situ*, our calculations give a negative answer. But our calculations suggest that during the capturing of asteroids into the Trojan orbits, their inclinations might be pumped up, mainly through close encounters with planets. After the capturing, there must be some braking mechanisms that can damp down the eccentricity but preserve the inclination.

## 5 Conclusions

The Trojan cloud around the triangular Lagrange points  $L_4, L_5$  of Neptune is believed to be a large reservoir of asteroids, hosting more asteroids than Jupiter’s Trojan cloud or even the main asteroid belt between Mars and Jupiter (Sheppard & Trujillo 2006, 2010b). Up to now, six leading Neptune Trojans around the  $L_4$  point and two trailing ones around the  $L_5$  point have been discovered. The dynamics of the  $L_4$  NTs have been studied in literatures by several authors (e.g. Marzari et al. 2003; Braser et al. 2004; Li et al. 2007; Horner & Lykawka 2010). In this paper, taking into account the errors introduced in the observations and orbital determinations, we investigate the orbital dynamics of two trailing NTs, 2004 KV18 and 2008 LC18. Starting from clouds of clone orbits around the nominal orbits, we simulate the clones’ orbital evolutions using the well-known *Mercury6* numerical integrator package.

Our results suggest that 2004 KV18 is on an especially unstable orbit. It is neither a primordial nor a permanent NT, but rather a passer-by object on its way of exchanging between a TNO and a Centaurs. Its lifetime as a trailing NT is in the order of  $10^5$  years in the future, and probably it has been on such a unstable tadpole orbit only for less than  $2 \times 10^5$  years. Such an unstable orbit means that it can neither be regard as the smoking gun of “the hot Trojan” from the chaotic capture model (Nesvorný & Vokrouhlický 2009) nor from the migrating Neptune model (Lykawka et al. 2009, 2010; Lykawka & Horner 2010).

Due to the strong chaos suffered by the orbits, it is hard to draw solid conclusion about where the asteroid came from and where it will go in the long term. But statistics on the clone orbits still give some helpful information, suggest that most probably it will evolve to be a TNO after its leaving the  $L_5$  region.

The asteroid 2008 LC18 however is more like a primordial trailing Neptune Trojan. Our calculations show that an appreciable proportion of clone orbits within the limits of orbital errors survives on the tadpole orbits for 4 Gyr and their orbital evolutions are very regular in both forward and backward time directions. Particularly, the high inclination of the orbit does not change much, implying that the orbit has not been excited on the tadpole orbit under current planetary configuration. On the contrary, for those clone orbits escaping from the tadpole orbit, their inclinations may vary significantly when they are outside of the Trojan phase. These calculations imply that the 2008 LC18 may be captured onto current high-inclined orbit very long ago, and during the capturing process its inclination may be excited due to close encounters with planets.

The orbital stability of clones of 2008 LC18 apparently depends on the semimajor axis and the

resonant angle. Nearly all the stable orbits are in a specific region of the  $(a, \sigma)$  plane, so we expect that additional observations will confine its orbit into this region.

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## References

- Bowell E., Holt H. E., Levy D. H., Innanen K. A., Mikkola S., Shoemaker E. M., 1990, BAAS, 22, 1357  
Braser R., Mikkola S., Huang T.-Y., Wiegert P., Innanen K., 2004, MNRAS, 347, 833  
Chambers J., 1999, MNRAS, 304, 793  
Chiang E. I., Jordan A. B., Millis R. L., et al., 2003, AJ, 126, 430  
Connors M., Wiegert P., Veillet C. 2011, Nature, 475, 481  
Crida A., 2009, arXiv:0903.3008  
Duncan M., Quinn T., Tremaine S., 1989, Icarus, 82, 402  
Dvorak R., Schwarzs R. Süli Á, Kotoulas T., 2007, MNRAS, 382, 1324  
Dvorak R., Bazso A., Zhou L.-Y., 2010, Celest. Mech. Dyn. Astron., 107, 51  
Dvorak R., Lhotka C., Zhou L.-Y., 2012, A&A, DOI: 10.1051/0004-6361/201118374  
Horner J., Lykawka P.S., 2010, MNRAS, 405, 49  
Li J., Zhou L.-Y., Sun Y.-S., 2007, A&A, 464, 775  
Lykawka P., Horner J., Jones B., Mukai T., 2009, MNRAS, 398, 1715  
Lykawka P., Horner J., Jones B., Mukai T., 2010, MNRAS, 404, 1272  
Lykawka P.S., Horner J., 2010, MNRAS, 405, 1375  
Mainzer, A., Bauer, J., Grav, T. and 32 coauthors, 2011, ApJ, 731, 53  
Marzari F., Tricarico P., Scholl H., 2003, A&A, 410, 725  
Michtchenko T., Ferraz-Mello S., 1995, A&A, 303, 945  
Morbidelli A., Levison H.F., Tsiganis K., Gomes R., 2005, Nature, 435 462  
Murray C.D., Demott S. F., 1999, Solar System Dynamics (New York: Cambridge Univ. Press)  
Nesvorný D., Dones L., 2002, Icarus, 160, 271  
Nesvorný D., Vokrouhlický D., 2009, AJ, 137, 5003  
Robutel P., Gabern F., 2006, MNRAS, 372, 1463  
Robutel P., Bodossian J., 2009, MNRAS, 399, 69  
Sheppard S., Trujillo C., 2006, Science, 313, 511  
Sheppard S., Trujillo C., 2010, Science, 329, 1304  
Sheppard S., Trujillo C., 2010, ApJ, 723, L233  
Wisdom J., 1980, AJ, 85, 1122  
Zhou L.-Y., Dvorak R., Sun Y.-S., 2009, MNRAS, 398, 1217  
Zhou L.-Y., Dvorak R., Sun Y.-S., 2011, MNRAS, 410, 1849